THE MISSISSIPPIAN LEADVILLE LIMESTONE EXPLORATION PLAY, UTAH AND COLORADO – EXPLORATION TECHNIQUES AND STUDIES FOR INDEPENDENTS

SEMI-ANNUAL TECHNICAL PROGRESS REPORT April 1, 2005 - September 30, 2005

by

Thomas C. Chidsey, Jr., Principal Investigator/Program Manager,
Utah Geological Survey,
David E. Eby, Eby Petrography & Consulting, Inc.,
and
John D. Humphrey, Colorado School of Mines

UTAH GEOLOGICAL SURVEY

January 2006

Contract No. DE-FC26-03NT15424

Virginia Weyland, Contract Manager
U.S. Department of Energy
National Petroleum Technology Office
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DISCLAIMER

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ABSTRACT

The Mississippian Leadville Limestone is a shallow, open-marine, carbonate-shelf deposit. The Leadville has produced over 53 million barrels (8.4 million m^3) of oil from six fields in the Paradox fold and fault belt of the Paradox Basin, Utah and Colorado. The environmentally sensitive, 7500-square-mile (19,400 km^2) area that makes up the fold and fault belt is relatively unexplored. Only independent producers operate and continue to hunt for Leadville oil targets in the region. The overall goal of this study is to assist these independents by (1) developing and demonstrating techniques and exploration methods never tried on the Leadville, (2) targeting areas for exploration, and (3) conducting a detailed reservoir characterization study. The final results will hopefully reduce exploration costs and risks, especially in environmentally sensitive areas, and add new oil discoveries and reserves.

This report covers research and technology transfer activities for the second half of the second project year (April 1, 2005 through September 30, 2005), Budget Periods I and II. This work consisted of finalizing diagenetic analysis (started during Budget Period I) of the Leadville Limestone reservoir at the Lisbon case-study field, Utah, which accounts for most of the Leadville oil production in the Paradox Basin. Research included (1) strontium and stable carbon/oxygen isotope analyses from Leadville core samples, and (2) interpretation of burial/ temperature history.

Stable carbon and oxygen isotope data indicate that all Lisbon field Leadville dolomites were likely associated with brines whose composition was enriched in del ^{18}O compared with late Mississippian seawater. The Leadville replacement dolomite's temperatures of precipitation ranged from about 140 to194^{o}F (~ 60 to 90^{o}C). Saddle dolomite cements were precipitated at temperatures greater that 194^{o}F (>90^{o}C).

High strontium isotopic ratios for Leadville late burial, diagenetic mineral phases indicate contributions by waters enriched in ^{87}Sr that were derived from either Precambrian granitic rocks or the Devonian McCracken Sandstone along basement-involved, high-angle normal faults. Brines from evaporates in the Pennsylvanian Paradox Formation may also entered the Leadville along the large fault bounding the northeast flank of the field.

Burial history and temperature profiles for the Leadville at Lisbon field provide some guidance as to when the important diagenetic events occurred. Porous replacement dolomites probably formed during the early and middle portions of the burial history. Inferred elevated temperature spikes during maximum burial, late Laramide faulting/uplift, and Oligocene igneous intrusive activity may account for the high temperatures responsible for quartz precipitation, sulfide mineralization, pyrobitumen formation, late dissolution of carbonates, and late saddle dolomite cements. We propose a model with thermal convection cells bounded by basement-rooted faults to transfer heat and fluids from possible granitic basement, Pennsylvanian evaporates, and Oligocene igneous complexes.

Technology transfer activities for the reporting period consisted of (1) exhibiting a booth display of project materials at the annual national and regional conventions of the American Association of Petroleum Geologists, (2) technical presentations summarizing the project objectives, Lisbon field characteristics, and Leadville dolomitization, and (3) publications. An abstract describing Leadville diagenesis with emphasis on dolomitization was submitted and accepted by the Geological Society of America, for presentation at the 2005 Annual Convention in Salt Lake City, Utah. The project home page was updated on the Utah Geological Survey Web site.

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EXECUTIVE SUMMARY

The Mississippian Leadville Limestone is a shallow, open-marine, carbonate-shelf deposit. The Leadville has produced over 53 million barrels (8.4 million m^3) of oil from six fields in the Paradox fold and fault belt of the Paradox Basin, Utah and Colorado. These fields are currently operated by small, independent producers. The environmentally sensitive, 7500-square-mile (19,400 km^2) area that makes up the fold and fault belt is relatively unexplored. Only independent operators continue to hunt for Leadville oil targets in the region. The overall goal of this study is to assist these independents by (1) developing and demonstrating techniques and exploration methods never tried on the Leadville Limestone, (2) targeting areas for exploration, and (3) conducting a detailed reservoir characterization study. The final results will hopefully reduce exploration costs and risk especially in environmentally sensitive areas, and add new oil discoveries and reserves.

To achieve this goal and carry out the Leadville Limestone study, the Utah Geological Survey (UGS) and Eby Petrography & Consulting, Inc., have entered into a cooperative agreement with the U.S. Department of Energy (DOE), National Petroleum Technology Office, Tulsa, Oklahoma. The research is funded as part of the DOE Advanced and Key Oilfield Technologies for Independents (Area 2 – Exploration) Program. This report covers research and technology transfer activities for the second half of the second project year (April 1, 2005 through September 30, 2005), Budget Periods I and II. This work consisted of diagenetic analysis of the Leadville Limestone reservoir at the Lisbon case-study field, Utah, which accounts for most of the Leadville oil production in the Paradox Basin. Research included (1) strontium and stable carbon/oxygen isotope analyses from Leadville core samples, and (2) interpretation of burial/temperature history.

Stable carbon and oxygen isotope data indicate that all Lisbon-field Leadville dolomites were likely associated with brines whose composition was enriched in del ^{18}O compared with Late Mississippian seawater (several per mil heavier than normal seawater). The Leadville replacement dolomite's temperatures of precipitation ranged from about 140 to194^{o}F (~ 60-90^{o}C. Saddle dolomite cements were precipitated at temperatures greater that 194^{o}F (>90^{o}C).

High strontium isotopic ratios for late burial diagenetic mineral phases at Lisbon field indicate contributions by waters enriched in ^{87}Sr that were derived from either Precambrian basement rocks or the Devonian McCracken Sandstone. Early Tertiary reactivation of basement-involved, high-angle normal faults associated with Precambrian tectonics may have allowed hot, deep-seated fluids from the granitic basement or the McCracken to communicate upwards with the Leadville carbonate section. Brines from evaporates in the Pennsylvanian Paradox Formation may also have entered the Leadville along the large fault bounding the northeast flank of the field.

Burial history and temperature profiles for the Leadville at Lisbon field provide some guidance as to when the important diagenetic events occurred. Porous replacement dolomites probably formed during the early and middle portions of the burial history at Lisbon field. Inferred elevated temperature spikes during maximum burial, late Laramide faulting/uplift, and Oligocene igneous intrusive activity may account for the high temperatures responsible for quartz precipitation, sulfide mineralization, pyrobitumen formation, late dissolution of carbonates, and late saddle dolomite cements. We propose a model with thermal convection cells bounded by basement-rooted faults to transfer heat and fluids from possible granitic basement, Pennsylvanian evaporates, and Oligocene igneous complexes.

Based on these results, we recommend that any evaluation of the Leadville Limestone include stable carbon and oxygen isotope analysis of diagenetic components, strontium isotope analysis for tracing the origin of fluids responsible for different diagenetic events, and production of burial history and temperature profiles to help determine when the diagenetic events occurred.

Technology transfer activities for the reporting period consisted of technical presentations, convention booth displays, and publications. Project materials, plans, objectives, and results were displayed at the Utah Geological Survey booth during the American Association of Petroleum Geologists (AAPG) Annual Convention, June 19-22, 2005, in Calgary, Canada, and at the AAPG Rocky Mountain Section Meeting, September 23-24, 2005, in Jackson, Wyoming. The presentations, made at the Calgary AAPG convention and a Society of Petroleum Engineers gas and oil development symposium in Salt Lake City, Utah, included a project overview, the general petroleum geology of the Leadville Limestone, facies, petrography, and diagenesis of the Lisbon case-study field in Utah. The project home page was updated on the Utah Geological Survey Web site. Project team members published an abstract and semi-annual report detailing project progress and results. An abstract describing Leadville diagenesis with emphasis on dolomitization was submitted and accepted for presentation at the 2005 Annual Convention of the Geological Society of America in Salt Lake City, Utah.

INTRODUCTION

Project Overview

The Mississippian Leadville Limestone has produced over 53 million barrels (bbls) (8.4 million m^3) of oil from six fields in the northern Paradox Basin region, referred to as the Paradox fold and fault belt, of Utah and Colorado. All of these fields are currently operated by small, independent producers. There have been no new discoveries since the early 1960s, and only independent producers continue to explore for Leadville oil targets in the region, 85 percent of which is under the stewardship of the federal government. This environmentally sensitive, 7500-square-mile (19,400 km^2) area is relatively unexplored with only about 100 exploratory wells that penetrated the Leadville (less than one well per township), and thus the potential for new discoveries remains great.

The overall goals of this study are to (1) develop and demonstrate techniques and exploration methods never tried on the Leadville Limestone, (2) target areas for exploration, (3) increase deliverability from new and old Leadville fields through detailed reservoir characterization, (4) reduce exploration costs and risk especially in environmentally sensitive areas, and (5) add new oil discoveries and reserves.

The Utah Geological Survey (UGS) and Eby Petrography & Consulting, Inc., have entered into a cooperative agreement with the U.S. Department of Energy (DOE) as part of its Advanced and Key Oilfield Technologies for Independents (Area 2 – Exploration) Program. The project is being conducted in two phases, each with specific objectives and separated by a continue-stop decision point based on results as of the end of Phase I (Budget Period I). The objective of Phase I was to conduct a case study of the Leadville reservoir at Lisbon field (the largest Leadville oil producer in the Paradox Basin), San Juan County, Utah, in order to understand the reservoir characteristics and facies that can be applied regionally. Phase I has been completed and Phase II (Budget Period II) approved by DOE. The first objective of Phase II will be to conduct a low-cost field demonstration of new exploration technologies to identify potential Leadville oil migration directions (evaluating the middle Paleozoic hydrodynamic pressure regime), and surface geochemical anomalies (using microbial, soil, gas, iodine, and trace elements), especially in environmentally sensitive areas. The second objective will be to determine regional facies (evaluating cores, geophysical well logs, outcrop and modern analogs), identify potential oil-prone areas based on shows (using low-cost epifluorescence techniques), and target areas for Leadville exploration.

These objectives are designed to assist the independent producers and explorers who have limited financial and personnel resources. All project maps, studies, and results will be publicly available in digital (interactive, menu-driven products on compact disc) or hard-copy format and presented to the petroleum industry through a proven technology transfer plan. The technology transfer plan includes a Technical Advisory Board composed of industry representatives operating in the Paradox Basin and a Stake Holders Board composed of representatives of state and federal government agencies, and groups with a financial interest within the study area. Project results will also be disseminated via the UGS Web site, technical workshops and seminars, field trips, technical presentations at national and regional professional meetings, convention displays, and papers in various technical or trade journals, and UGS publications.

This report covers research and technology transfer activities for the second half of the second project year (April 1, 2005 through September 30, 2005), Budget Periods I and II. This work consisted of diagenetic analysis of the Leadville Limestone reservoir at the Lisbon case-study field, Utah. Research included (1) strontium and stable carbon/oxygen isotopes analyses from Leadville core samples, and (2) interpretation of burial/temperature history.

Project Benefits and Potential Application

Exploring for the Leadville Limestone is high risk, with less than a 10 percent chance of success based on the drilling history of the region. Prospect definition requires expensive, three-dimensional (3D) seismic acquisition, often in environmentally sensitive areas. These facts make exploring difficult for independents that have limited funds available to try new, unproven techniques that might increase the chance of successfully discovering oil. We believe that one or more of the project activities will reduce the risk taken by an independent producer in looking for Leadville oil, not only in exploring but in trying new techniques. For example, the independent would not likely attempt surface geochemical surveys without first knowing they have been proven successful in the region. If we can prove geochemical surveys are an effective technique in environmentally sensitive areas, the independent will save both time and money exploring for Leadville oil.

Another problem in exploring for oil in the Leadville Limestone is the lack of published or publicly available geologic and reservoir information, such as regional facies maps, complete reservoir characterization studies, surface geochemical surveys, regional hydrodynamic pressure regime maps, and oil show data and migration interpretations. Acquiring this information or producing these studies would save cash and manpower resources which independents simply do not possess or normally have available only for drilling. The technology, maps, and studies generated from this project will help independents to identify or eliminate areas and exploration targets prior to spending significant financial resources on seismic data acquisition and environmental litigation, and therefore increase the chance of successfully finding new accumulations of Leadville oil.

These benefits may also apply to other high-risk, sparsely drilled basins or regions where there are potential shallow-marine carbonate reservoirs equivalent to the Mississippian Leadville Limestone. These areas include the Utah-Wyoming-Montana thrust belt (Madison Limestone), the Kaiparowits Basin in southern Utah (Redwall Limestone), the Basin and Range Province of Nevada and western Utah (various Mississippian and other Paleozoic units), and the Eagle Basin of Colorado (various Mississippian and other Paleozoic units).

Many mature basins have productive carbonate reservoirs of shallow-marine shelf origin. These mature basins include the Eastern Shelf of the Midland Basin, West Texas (Pennsylvanian-age reservoirs in the Strawn, Canyon, and Cisco Formations); the Permian Basin, West Texas and southeast New Mexico (Permian age Abo and other formations along the northwest shelf of the Permian Basin); and the Illinois Basin (various Silurian units). A successful demonstration in the Paradox Basin makes it very likely that the same techniques could be applied in other basins as well. In general, the average field size in these other mature basins is larger than fields in the Paradox Basin. Even though there are differences in depositional facies and structural styles between the Paradox Basin and other basins, the fundamental use of the techniques and methods is a critical commonality.

PARADOX BASIN - OVERVIEW

The Paradox Basin is located mainly in southeastern Utah and southwestern Colorado, with a small portion in northeastern Arizona and northwestern New Mexico (figure 1). The Paradox Basin is an elongate, northwest-southeast-trending, evaporitic basin that predominately developed during the Pennsylvanian. The basin can generally be divided into three areas: the Paradox fold and fault belt in the north, the Blanding sub-basin in the south-southwest, and the Aneth platform in southeasternmost Utah (figure 1). The Mississippian Leadville Limestone is one of two major oil and gas reservoirs in the Paradox Basin, the other being the Pennsylvanian Paradox Formation (figure 2); minor amounts of oil are produced from the Devonian McCracken Sandstone at Lisbon field. Most Leadville production is from the Paradox fold and fault belt (figure 3).

The most obvious structural features in the basin are the spectacular anticlines that extend for miles in the northwesterly trending fold and fault belt. The events that caused these and many other structural features to form began in the Proterozoic, when movement initiated on high-angle basement faults and fractures 1700 to 1600 Ma (Stevenson and Baars, 1987). During Cambrian through Mississippian time, this region, as well as most of eastern Utah, was the site of typical, thin, marine deposition on the craton while thick deposits accumulated in the miogeocline to the west (Hintze, 1993). However, major changes occurred beginning in the Pennsylvanian. A series of basins and fault-bounded uplifts developed from Utah to Oklahoma as a result of the collision of South America, Africa, and southeastern North America (Kluth and Coney, 1981; Kluth, 1986), or from a smaller scale collision of a microcontinent with south-central North America (Harry and Mickus, 1998). One result of this tectonic event was the uplift of the Ancestral Rockies in the western United States. The Uncompahgre Highlands in eastern Utah and western Colorado initially formed as the westernmost range of the Ancestral Rockies during this ancient mountain-building period. The southwestern flank of the Uncompahgre Highlands (uplift) is bounded by a large, basement-involved, high-angle, reverse fault identified from seismic surveys and exploration drilling. As the highlands rose, an accompanying depression, or foreland basin, formed to the southwest – the Paradox Basin. Rapid subsidence, particularly during the Pennsylvanian and continuing into the Permian, accommodated large volumes of evaporitic and marine sediments that intertongue with non-marine arkosic material shed from the highland area to the northeast (Hintze, 1993).

The Paradox Basin is surrounded by other uplifts and basins, which formed during the Late Cretaceous-early Tertiary Laramide orogeny (figure 1). The Paradox fold and fault belt was created during the Tertiary and Quaternary by a combination of (1) reactivation of basement normal faults, (2) salt flowage, dissolution, and collapse, and (3) regional uplift (Doelling, 2000).

Most oil and gas produced from the Leadville Limestone is found in basement-involved, northwest-trending structural traps with closure on both anticlines and faults (figure 4). Lisbon, Big Indian, Little Valley, and Lisbon Southeast fields (figure 3) are sharply folded anticlines that close against the Lisbon fault zone. Salt Wash and Big Flat fields (figure 3), northwest of the Lisbon area, are unfaulted, east-west- and north-south-trending anticlines, respectively.

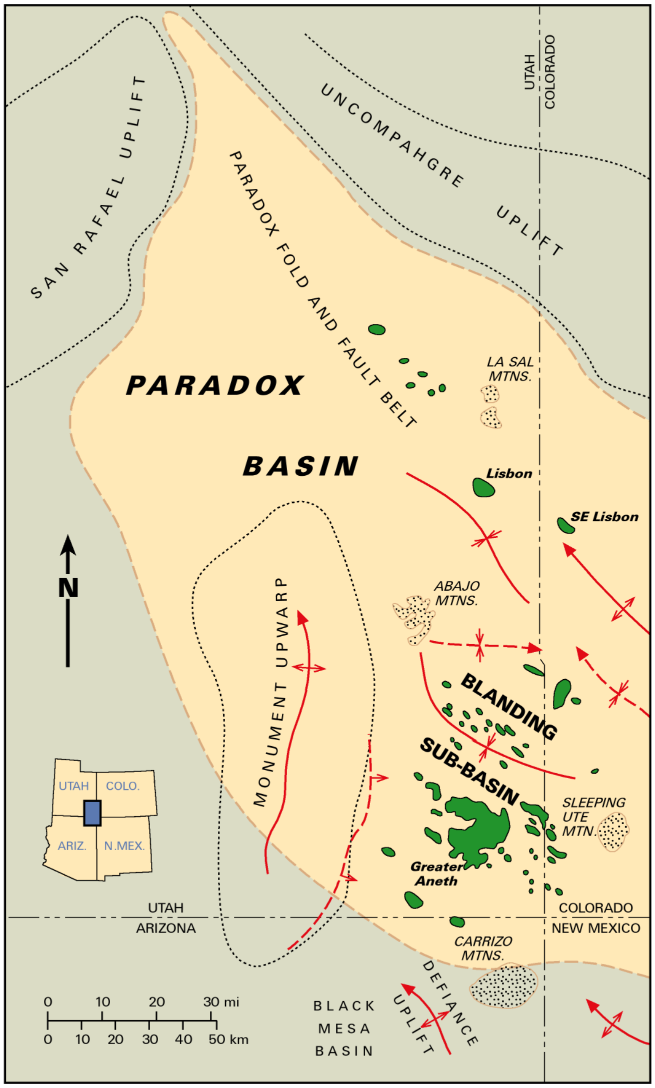

Figure 1. Oil and gas fields in the Paradox Basin of Utah and Colorado.

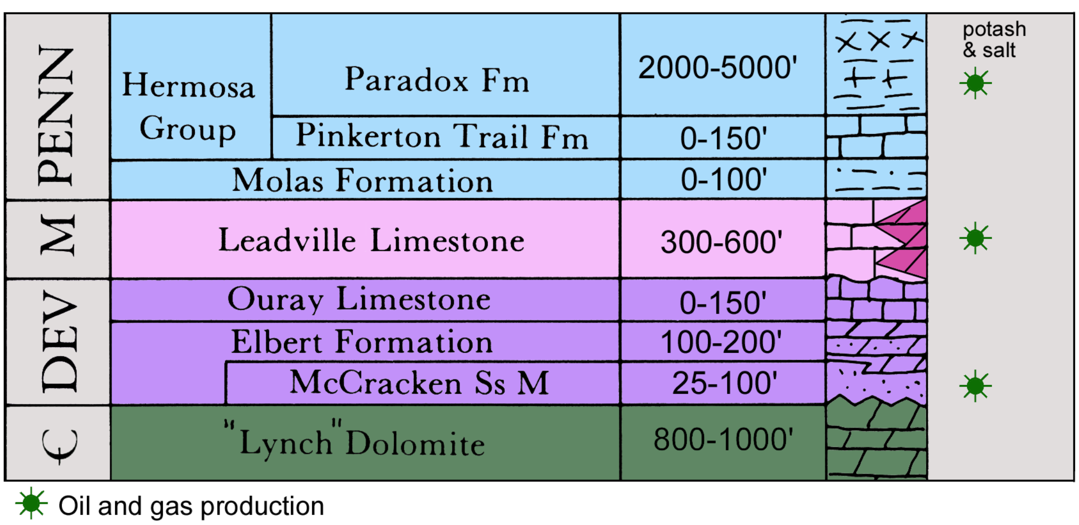

Figure 2. Stratigraphic column of a portion of the Paleozoic section determined from subsurface well data in the Paradox fold and fault belt, Grand and San Juan Counties, Utah (modified from Hintze, 1993).

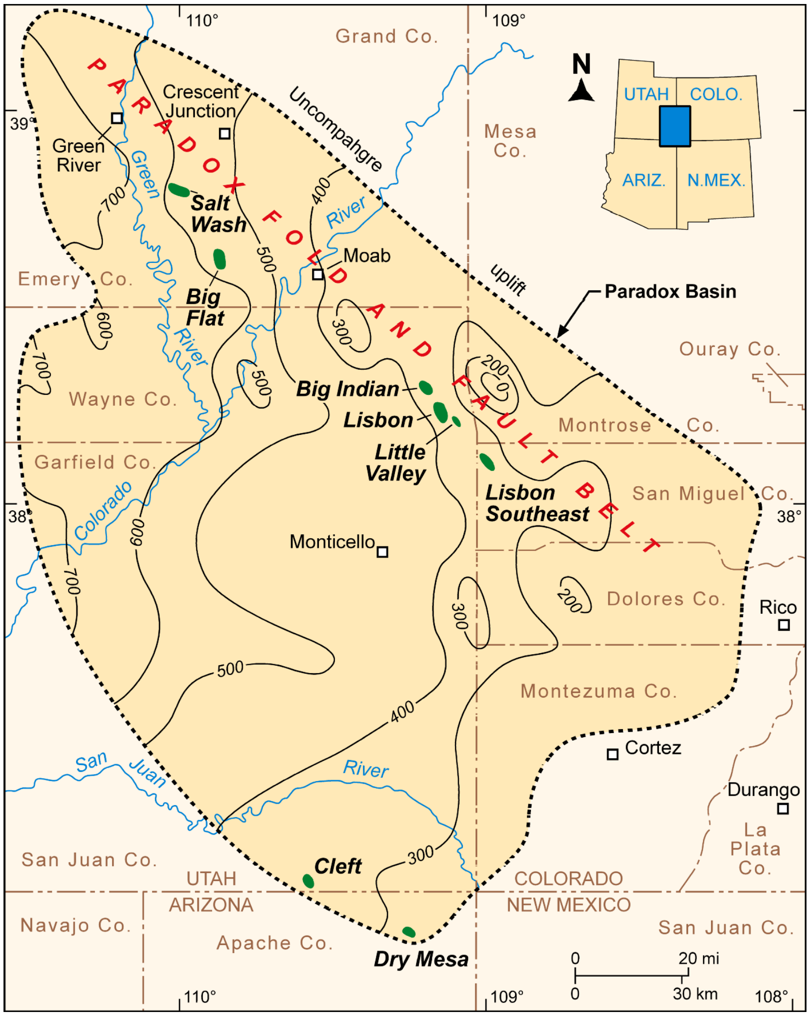

Figure 3. Location of fields that produce oil (green) from the Mississippian Leadville Limestone, Utah and Colorado. Thickness of the Leadville is shown; contour interval is 100 feet (modified from Parker and Roberts, 1963).

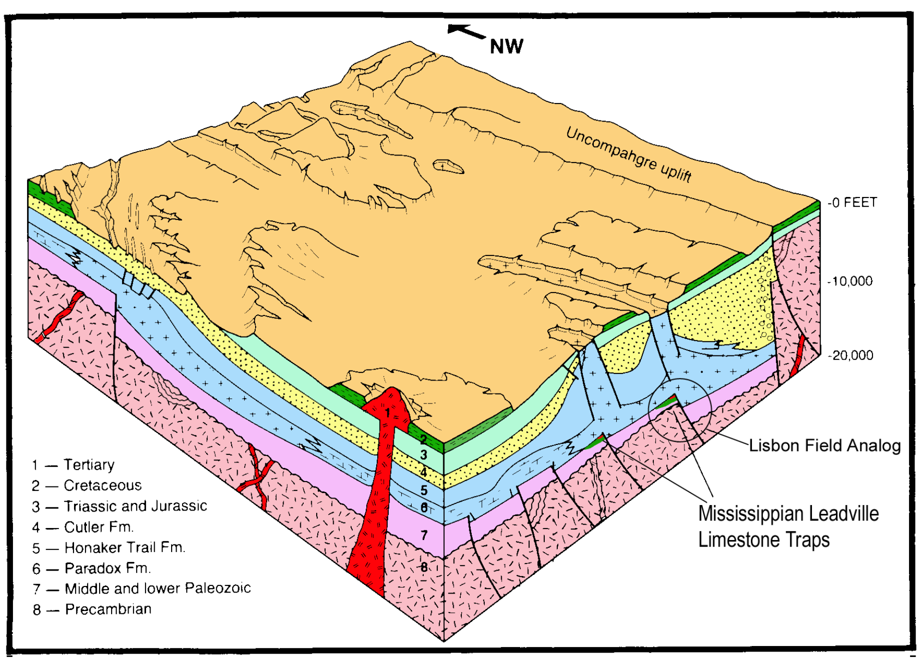

Figure 4. Schematic block diagram of the Paradox Basin displaying basement-involved structural trapping mechanisms for the Leadville Limestone fields (modified from Petroleum Information, 1984; original drawing by J.A. Fallin).

RESERVOIR CHARACTERIZATION OF THE LEADVILLE LIMESTONE, LISBON CASE-STUDY FIELD, SAN JUAN COUNTY, UTAH – RESULTS AND DISCUSSION

Introduction and Field Synopsis

Lisbon field, San Juan County, Utah (figure 3) accounts for most of the Leadville oil production in the Paradox Basin. A wealth of Lisbon core, petrographic, and other data is available to the UGS. The reservoir characteristics, particularly diagenetic overprinting and history, and Leadville facies can be applied regionally to other fields and exploration trends in the Paradox Basin. Therefore, we selected Lisbon as the major case-study field for the Leadville Limestone project.

The Lisbon trap is an elongate, asymmetric, northwest-trending anticline, with nearly 2000 feet (600 m) of structural closure and bounded on the northeast flank by a major, basement-involved normal fault with over 2500 feet (760 m) of displacement (Smith and Prather, 1981) (figure 5). Several minor, northeast-trending normal faults divide the Leadville reservoir into segments. Producing units contain dolomitized crinoidal/skeletal grainstone, packstone, and wackestone fabrics. Diagenesis includes fracturing, autobrecciation, karst

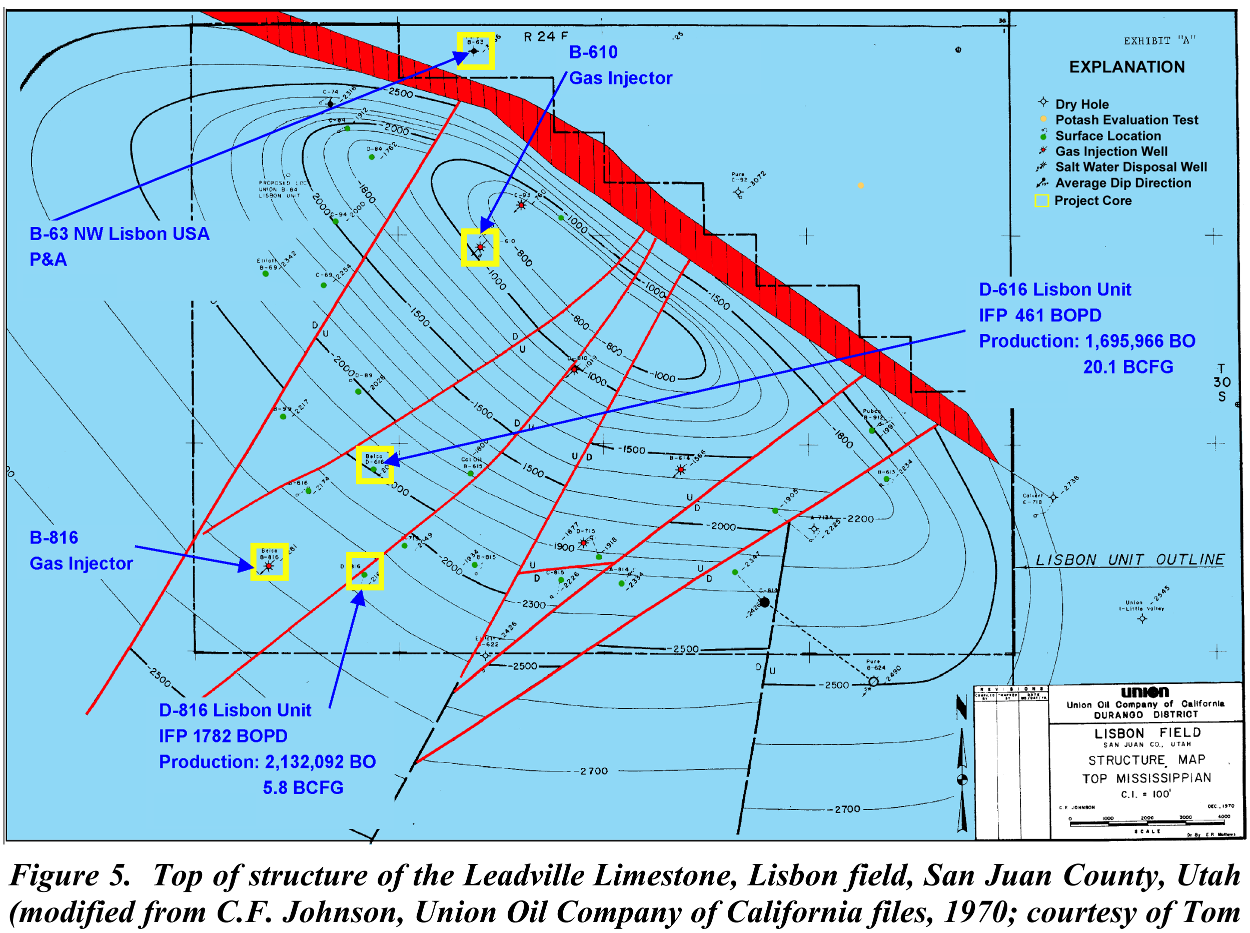

Figure 5. Top of structure of the Leadville Limestone, Lisbon field, San Juan County, Utah (modified from C.F. Johnson, Union Oil Company of California files, 1970; courtesy of Tom Brown, Inc.). Also displayed are wells from which cores were described and sampled in this study.

development, hydrothermal dolomite, and bitumen plugging. The net reservoir thickness is 225 feet (69 m) over a 5120-acre (2100 ha) area (Clark, 1978; Smouse, 1993). Reservoir quality is greatly improved by natural fracture systems associated with the Paradox fold and fault belt. Porosity averages 6 percent in intercrystalline and moldic networks enhanced by fractures; permeability averages 22 millidarcies (mD). The drive mechanism is an expanding gas cap and gravity drainage; water saturation is 39 percent (Clark, 1978; Smouse, 1993). The bottom-hole temperature ranges from 153 to 189ºF (67-87ºC).

Lisbon field was discovered in 1960 with the completion of the Pure Oil Company No. 1 NW Lisbon USA well, NE1/4NW1/4 section 10, T. 30 S., R. 24 E., Salt Lake Base Line and Meridian (figure 5), with an initial flowing potential of 179 bbls of oil per day (28 m^3) and 4376 thousand cubic feet of gas per day (124 MCMPD). The original reservoir field pressure was 2982 pounds per square inch (20,560 kPa) (Clark, 1978). There are currently 22 producing (or shut-in wells), 11 abandoned producers, five injection wells (four gas injection wells and one water/gas injection well), and four dry holes in the field. Cumulative production as of September 1, 2005, was 51,131,973 bbls of oil (8,129,984 m^3), 780.7 billion cubic feet of gas (22.1 BCMG) (cycled gas), and 49,966,916 bbls of water (7,944,740 m^3) (Utah Division of Oil, Gas and Mining, 2005). Gas that was re-injected into the crest of the structure to control pressure decline is now being produced.

Three factors create reservoir heterogeneity within productive zones: (1) variations in carbonate fabrics and facies, (2) diagenesis (including karstification), and (3) fracturing. The extent of these factors and how they are combined affect the degree to which they create barriers to fluid flow.

Diagenetic Analysis - Overview

The diagenetic fabrics and porosity types found in the various hydrocarbon-bearing rocks of Lisbon field can be indicators of reservoir flow capacity, storage capacity, and untested potential. Diagenetic characterization focused on reservoir heterogeneity, quality, and compartmentalization within the field. All depositional, diagenetic, and porosity information will be combined with the production history in order to analyze the potential for the Leadville regionally. In order to determine the diagenetic histories of the various Leadville rock fabrics, including both reservoir and non-reservoir, representative samples were selected from the conventional cores for petrographic description and geochemical analysis.

Diagenesis played a major role in the development of reservoir heterogeneity in Lisbon field as well as throughout all of the Leadville fields. An ideal diagenetic sequence based on our analysis of Leadville thin sections from Lisbon field is presented in figure 6. Diagenetic processes started during deposition and continued throughout burial history. A complete discussion on the diagenetic history based upon visual core examination, thin-section petrography, scanning electron microscopy, epifluorescence, cathodoluminescence, and fluid inclusions was documented previously by Chidsey and others (2005a, 2005b). Leadville reservoir quality at Lisbon is greatly enhanced by dolomitization and dissolution of limestone. There are two basic types of dolomite: very fine, early dolomite and coarse, late dolomite. The early dolomitization and leaching of skeletal grains resulted in low-porosity and/or low-permeablility rocks. Most reservoir rocks within Lisbon field appear to be associated with the second, late type of dolomitization and associated leaching events. Other diagenetic products include pyrobitumen, syntaxial cement, sulfide minerals, anhydrite cement and replacement,

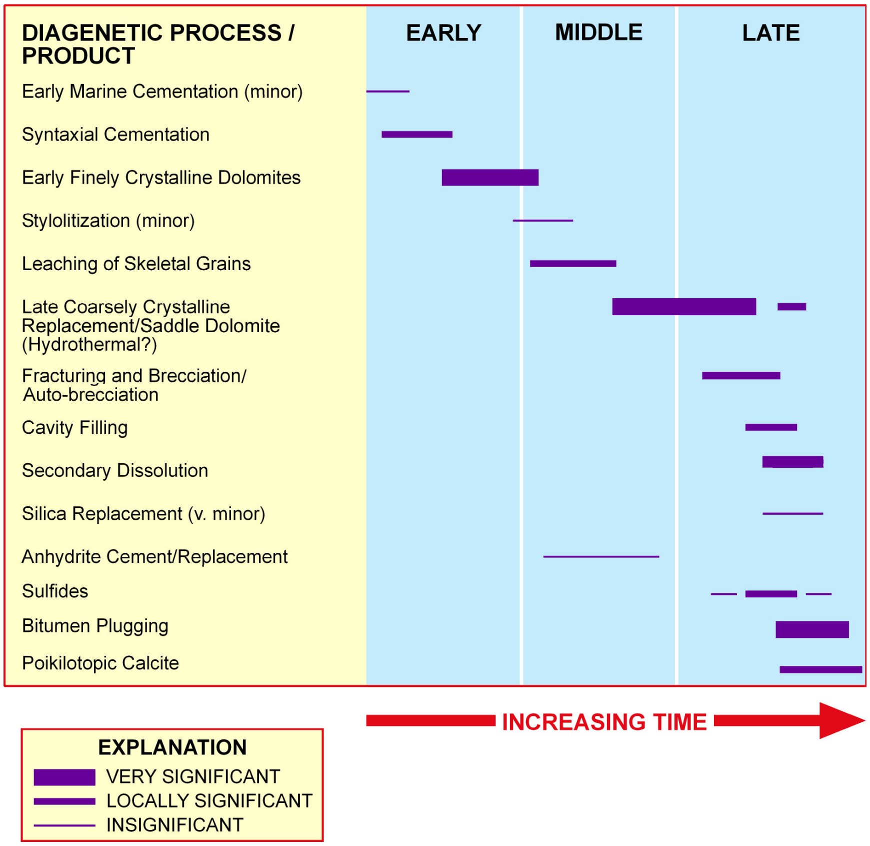

Figure 6. Ideal diagenetic sequence through time based on thin section analysis, Leadville Limestone, Lisbon field.

and late macrocalcite. Fracturing and brecciation caused by hydrofracturing are widespread within Lisbon field. Sediment-filled cavities, related to karstification of the exposed Leadville, are present in the upper third of the formation. Late dolomitization, sulfides, and brecciation may have developed from hydrothermal events that can greatly improve reservoir quality.

The geochemical analyses described in this report include (1) stable carbon and oxygen isotope analysis of diagenetic components such as cementing minerals and different generations of dolomites, and (2) strontium isotope analysis for tracing the origin of fluids responsible for different diagenetic events.

Stable Carbon and Oxygen Isotope Analysis

Introduction

Modification of rock fabrics and porosity within the Leadville Limestone in Lisbon field is quite complex. Stable isotope geochemistry has been used in recent years to provide insights into the chemical differences between preserved remnants of depositional components and the various diagenetic events in carbonate rocks, as recognized from core examination and thin section petrography. Figure 7 shows a graph of carbon versus oxygen isotope compositions for a range of carbonate rock types from various published sources compiled by Roylance (1990). Broad fields of carbon and oxygen isotope compositions for various carbonate rock settings are indicated, including modern marine ("subsea") cements, various marine skeletons and sediments, deep-water ("pelagic") limestone, Pleistocene carbonates, and meteoric carbonates ("speleothems and veins").

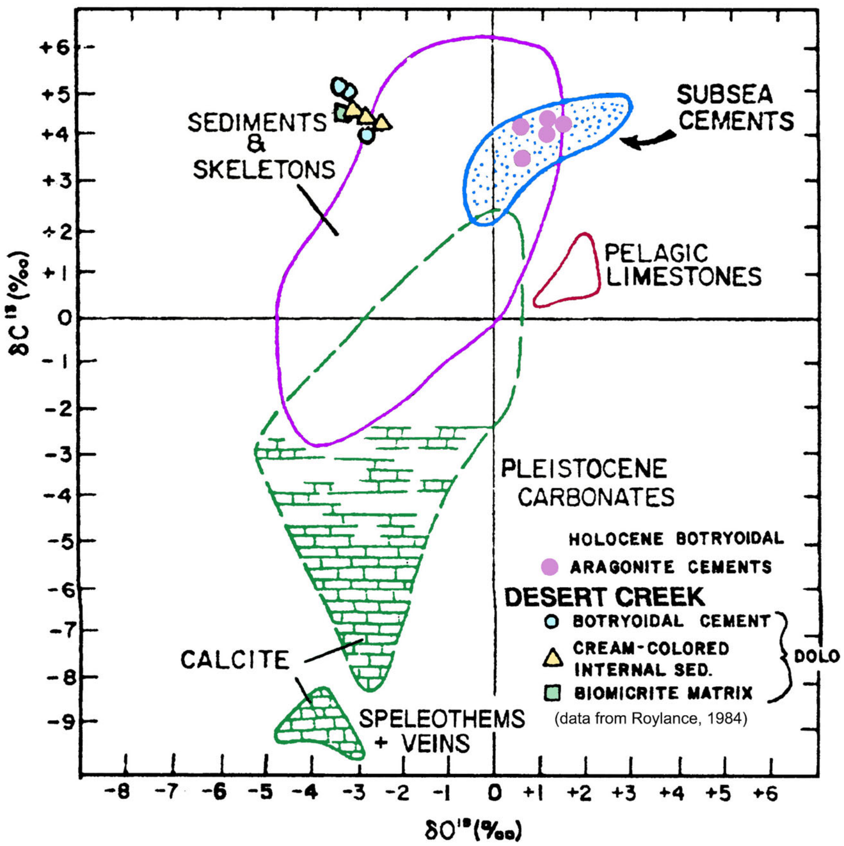

Figure 7. Graph of carbon versus oxygen isotope compositions. Other compositional facies compiled from various published work (modified from James and Ginsburg, 1979, by Roylance, 1990).

Methodology

Isotopic composition analyses for stable carbon and oxygen, as well as strontium, were completed on a variety of diagenetic phases from Lisbon field core samples (table 1). Individual samples were collected as powdered rock using a Dremel drill equipped with precision bits.

All analyses were completed at the Colorado School of Mines (CSM) Stable Isotope Laboratory, Golden, Colorado. The CSM lab possesses the capabilities of analyzing the stable isotopes of hydrogen, carbon, nitrogen, oxygen, and sulfur (H, C, N, O, and S) from a wide array of sample matrices. The GV Instruments IsoPrime mass spectrometer (figure 8) is the keystone around which several on-line preparation devices operate. Traditional dual-inlet applications (waters, carbonates, off-line prepared gases) are prepared with a MultiPrep auto sampler capable of performing carbon dioxide (CO_2) and H_2 equilibration on water samples, and acid digestion of carbonate samples (figure 9). A 50-port manifold can also be fitted for dual-inlet analysis of off-line gases. The IsoPrime mass spectrometer is also interfaced with continuous-flow preparation devices, including two elemental analyzers and a trace-gas preconcentrator. The elemental analyzers generate gases by combustion or pyrolysis, which are then carried in an inert stream of helium to the mass spectrometer for analysis of H, C, N, O, and S. Common applications include analysis of phosphates, nitrates, waters, organics, soils, plant and animal matter, sulfides, sulfates, and oils. The trace-gas preconcentrator cryogenically focuses trace quantities of gases for isotopic analysis. Common applications include analysis of methane, carbon dioxide, and nitrous oxide from atmospheric and soil-gas samples.

Table 1. Stable carbon and oxygen isotope data from the Mississippian Leadville Limestone, Lisbon field core samples.

Sample No.	Well	Depth (ft)	del ^{13}C	del ^{18}O	Comments
1	B-63	9960.6	-2.441	-6.830	Late calcite
2	B-63	9960.6	-1.918	-1.435	Syngenetic dolomite
3	B-63	10,004-05	-6.092	-11.297	Late calcite
4	D-816	8444-45	-2.696	-3.069	Dolomite cement
5	D-816	8444-45	-2.648	-2.441	Replacement dolomite
6	D-816	8444-45	-3.008	-2.287	Matrix dolomite
7	D-816	8421	-2.584	-3.699	Dolomite cement
8	D-816	8421	-2.978	-4.265	Replacement dolomite
9	D-616	8356-57	-3.709	-4.613	Saddle dolomite in fractures
10	D-616	8356-57	-2.793	-4.422	Limestone matrix/crinoids
11	D-816	8433	-2.815	-3.375	Late replacement matrix dolomite
12	B-610	7897	-2.951	-0.963	White, tight early dolomite
13	B-610	7897	-3.348	-2.808	Black, porous late dolomite
14	B-610	7886	-3.294	-2.601	White, tight early dolomite
15	B-610	7886	-3.126	-2.890	Black, porous late dolomite
16	D-616	8559	-2.851	-3.313	Black, porous late replacement dolomite
17	D-616	8682	4.407	-2.086	Syngenetic dolomite
18	B-63	9935.6	-2.795	-4.012	Dolomite (possible cross-cutting karst sediment fill)
19	B-63	9935.6	-2.785	-5.564	Limestone, peloidal/skeletal grainstone; sampled only black non-skeletal grains which appear microporous
20	D-616	8308-09	-4.418	-3.038	Dolomitized sediment within karst cavity
21	D-616	8308-09	-2.783	-4.147	Limestone country rock
22	B-63	9991.8	-3.510	-7.668	Late calcite, poikliotopic
23	B-63	9939	-3.499	-7.644	Saddle dolomite
24	B-63	9909	-4.794	-12.255	Late calcite
25	D-616	8308	-4.224	-2.694	Karst-fill dolomite

The internal standard used in the CSM lab is the University of Californian at Los Angeles (UCLA) Carrara marble. The accepted values for this internal standard were matched consistently during the analysis of the Leadville core samples selected for this study. All isotopic compositions are reported relative to PeeDee Belemnite (PDB) (see Land, 1980, figure 6 for definition relative to Standard Mean Ocean Water [SMOW]).

Figure 8. The CSM Stable Isotope Laboratory's GV Instruments IsoPrime stable isotope ratio mass spectrometer. Several peripheral devices are interfaced with the IsoPrime for both dual-inlet and continuous flow applications.

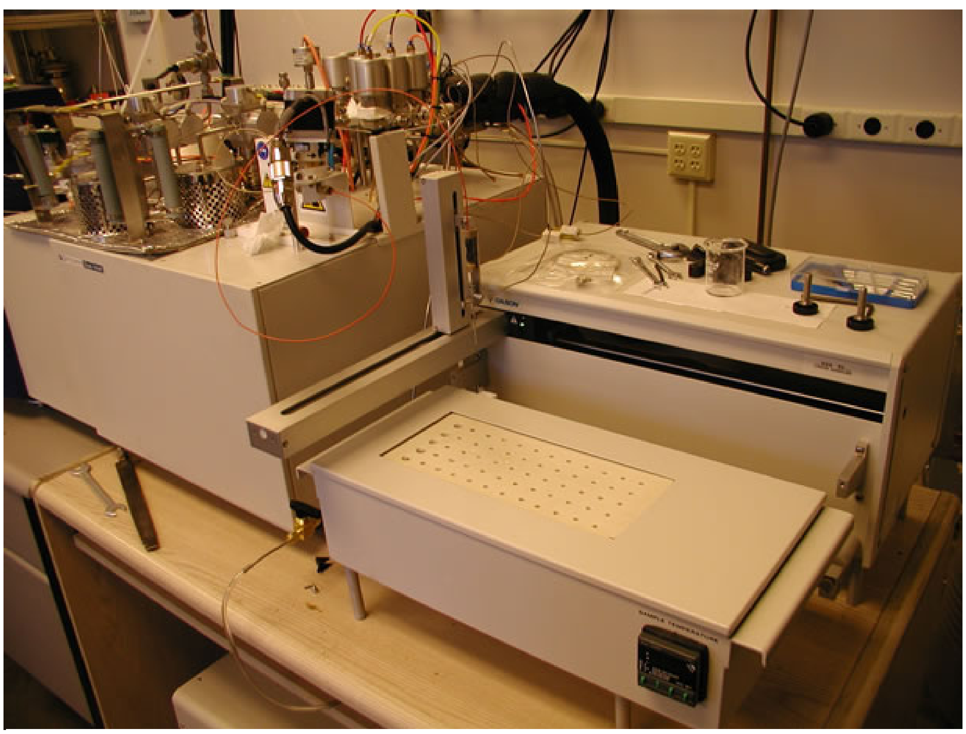

Figure 9. MultiPrep intended for high-precision dual-inlet analysis of carbon and oxygen isotopes of carbonate samples, and oxygen isotopes for waters by traditional equilibration techniques. Sample sizes for carbonates ranges from 10 to 100 ug – water samples are 200 ul.

Stable Carbon and Oxygen Isotopes for Leadville Samples at Lisbon Field

Carbon isotopic compositions for the 25 Leadville Limestone (limestone and dolomite) samples from Lisbon field (table 1 and figure 10) cluster in a very narrow range around the mean value of –2.95‰ PDB; the range is –1.92 to –6.09‰ PDB (one notable exception of +4.4‰ was excluded). Oxygen isotopic compositions for these samples, however, are more widespread (table 1 and figure 10). The range is –0.96 to –12.26‰ PDB; the mean value is –4.61‰ PDB.

Stable carbon and oxygen isotope data indicate that all Lisbon Leadville dolomites were likely associated with brines whose composition was enriched in del ^{18}O compared with Late Mississippian seawater. Stable oxygen isotope analyses of dolomites show a linear trend with a fairly narrow range of carbon isotope values (figure 10). Figure 11 shows a cross plot of the same del ^{13}C/del ^{18}O Leadville data from Lisbon field with the regions of dolomite temperatures of formation suggested by Allan and Wiggins (1993), based upon their interpretation of many ancient dolomites. Note that most of the Leadville data points plot in the region that Allan and Wiggins have called the "overlap of low and high temperature dolomites."

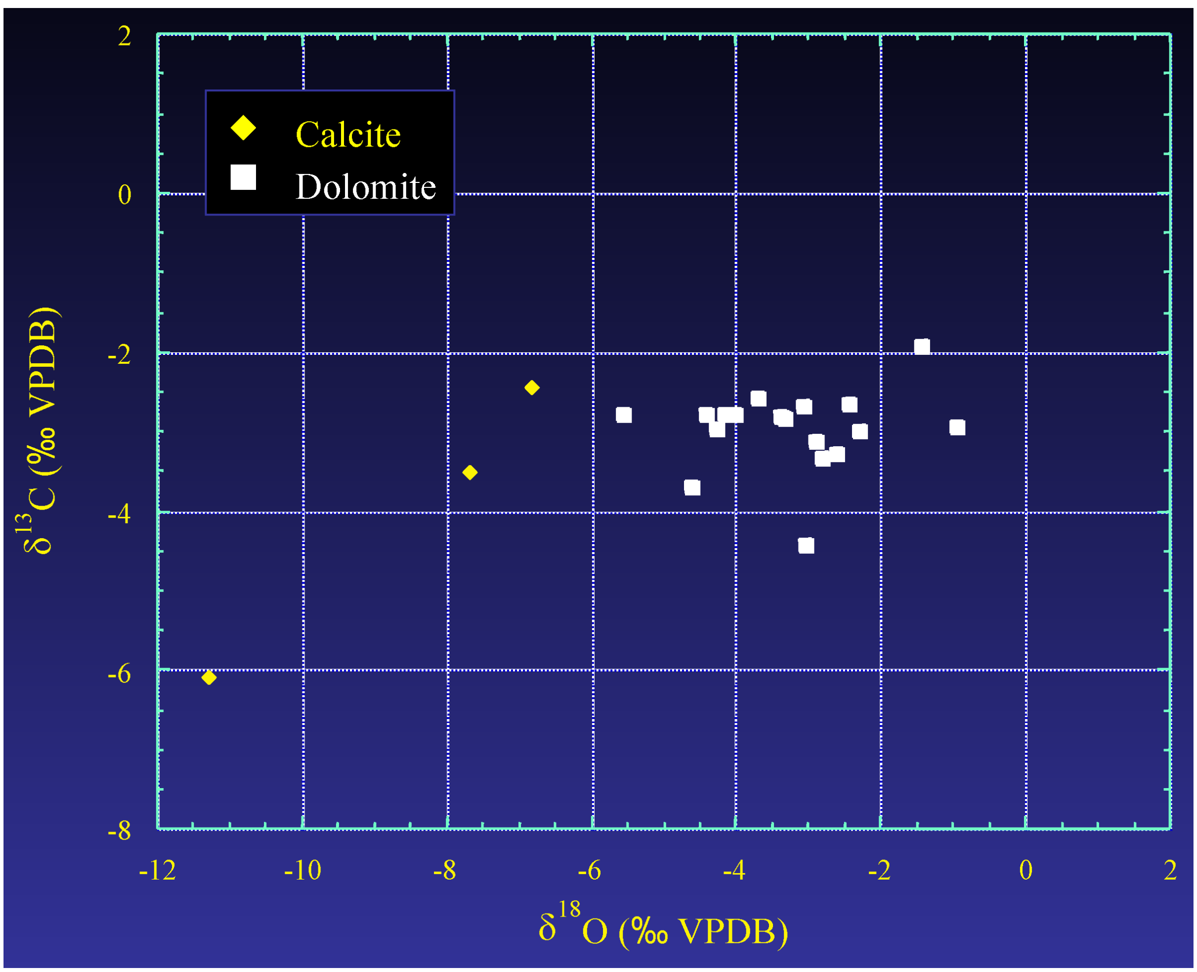

Figure 10. Graph of stable carbon versus oxygen isotopic compositions for Leadville dolomite and calcite from Lisbon field. Sample number 24 not shown.

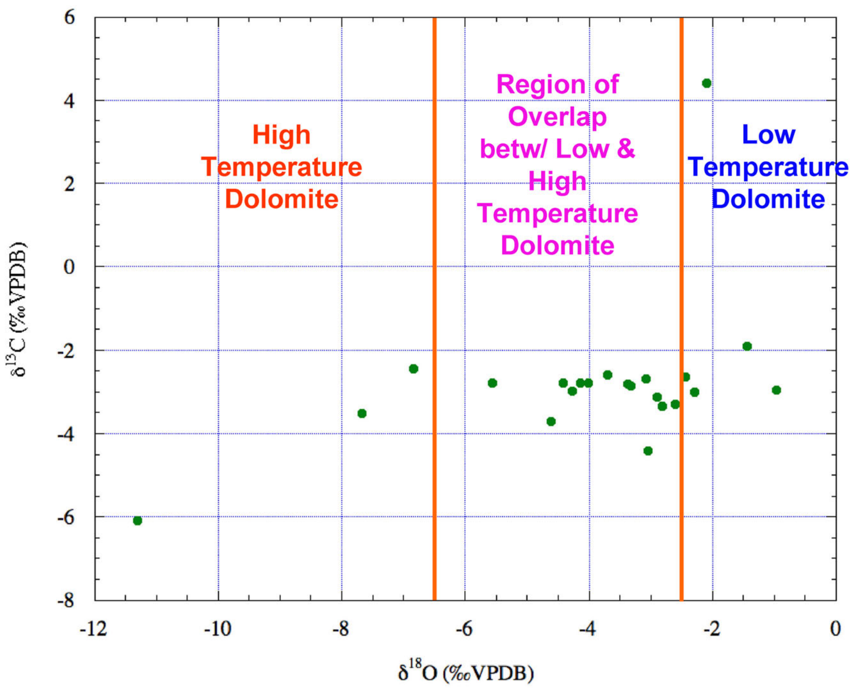

Figure 11. Cross plot of the del ^{13}C/del ^{18}O Leadville data from Lisbon field with the regions of dolomite temperatures of formation suggested by Allan and Wiggins (1993).

Stable oxygen isotopes for Mississippian seawater were in the range of –2 to –1‰ (Veizer and others, 1999). Dolomitizing fluid compositions enriched with respect to del ^{18}O are thought to be heavier than normal Mississippian seawater (bracketed by the yellow arrows on figure 12). Leadville reflux dolomitization likely resulted from evaporated brines, several per mil heavier than normal seawater (for example modern Arabian Gulf water in the range of 2.5 to 4‰ (Wood and others, 2002). Assuming similar oxygen enrichment of Mississippian seawater values gives a dolomitizing fluid in the range of 0.5 to 3‰. This factor, coupled with Leadville dolomite isotope values, constrain Leadville replacement dolomitization temperatures to between 140 and 194°F (60-90°C) (figure 12). Saddle dolomite cements were precipitated at temperatures greater that 194°F (>90°C).

Strontium Isotope Analysis

Introduction

Strontium (Sr) isotope analysis was used to assist with the diagenetic interpretation of different subsurface mineral phases within Leadville Limestone samples from Lisbon field. The interpretation of these analyses will be discussed after the following comments about the nature of the Sr isotope analysis, as well as a description of the analytical technique and laboratory used.

Applications and Background

Strontium isotope analysis is used most frequently as an age-dating tool in marine carbonates. The Sr composition of ancient seawater and its variation through geologic time have been determined from common marine carbonate minerals, especially calcite, aragonite, and dolomite (Brass, 1976; Burke and others, 1982; Allan and Wiggins, 1993).

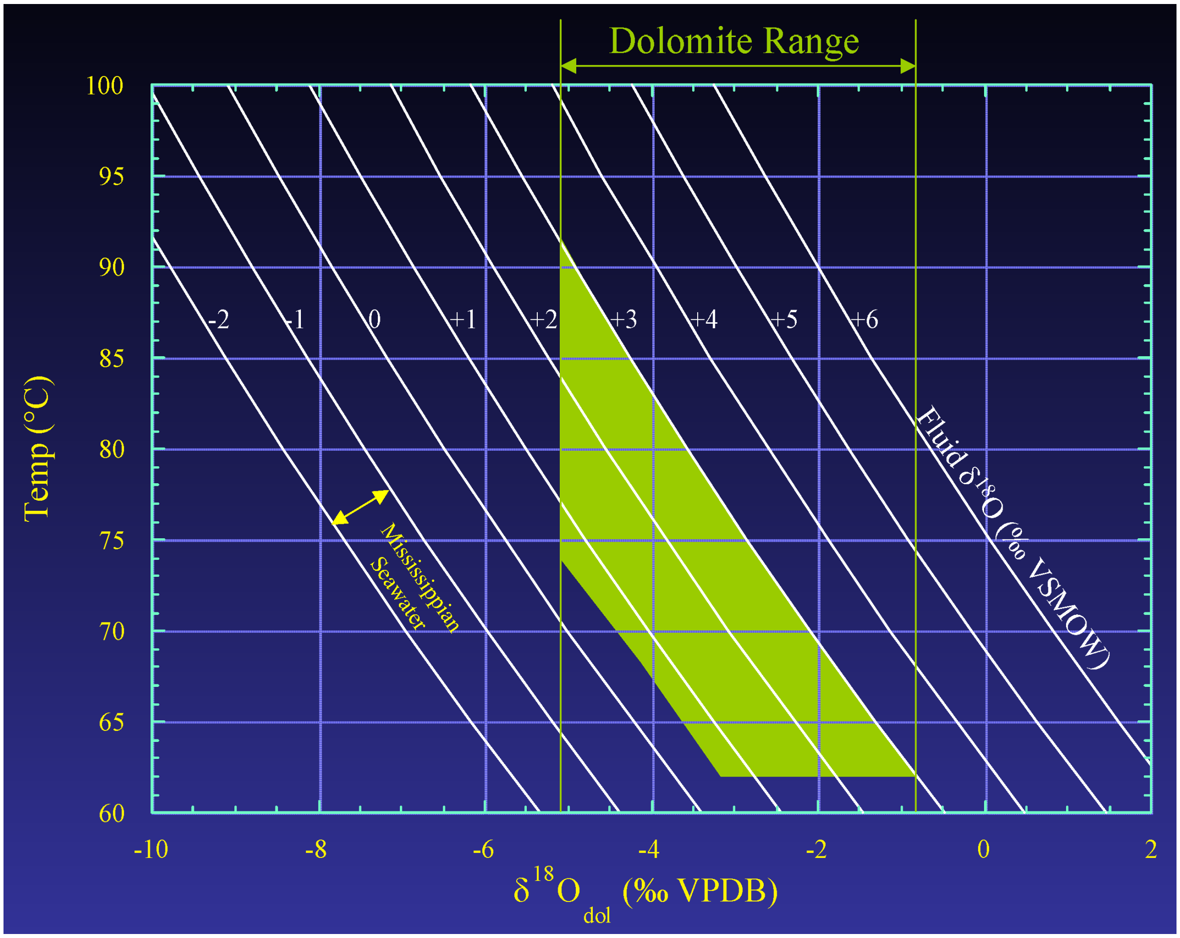

Figure 12. Graph of dolomite stable oxygen isotope values versus temperature data. The green field shows our estimate of del ^{18}O of dolomitzing fluids at between 0.5 and 3.0‰. Precipitation temperatures were up to about 90^{o}C (~194°F).

Among the four known isotopes of Sr, the ratio of $^{87}Sr/^{86}Sr$ is the most useful for tracking the secular changes of seawater Sr. These two isotopes come from separate sources in the earth. Strontium 87 is radiogenic (from the radioactive decay of rubidium 87 with a half-life of about 50 billion years), while ^{86}Sr is non-radiogenic (Faure and Powell, 1972; Faure, 1977). These secular changes in the Sr ratio of seawater are the result of the interplay of tectonism and erosion versus seafloor spreading (Allan and Wiggins, 1993). In general, erosion resulting from increased tectonism increases the ratio of $^{87}Sr/^{86}Sr$; during times of high seafloor spreading the ratio is decreased. The assumed reason for these changes is that continental (sialic) crustal rocks (for example granites, gneisses, and their derivatives such as arkoses) contribute radiogenic Sr ratios (that is relatively high Sr isotopic numbers). On the other hand, mantle (simatic) rocks (for example basalts, other volcanic, undifferentiated basic rock types, and their derivatives such as lithic sandstones) are much less radiogenic (that is relatively low Sr isotopic ratios). The high contribution of Sr into the oceans from highly radiogenic continental materials and less radiogenic mantle minerals, combined with the rapid mixing rate of the oceans and the long oceanic residence time of Sr, have allowed the Sr isotope ratio of seawater to be the same globally at any given time. For useful discussions and explanations of these factors, see (Veizer, 1989; and Allan and Wiggins, 1993, p. 49-52).

Most workers believe that the Sr isotopic composition of seawater throughout the world has changed through geologic time as a function of the relative fluxes in contributions from mantle and continental Sr. The mantle contributions are highest during times of rapid seafloor spreading. The continental contributions are highest during times of orogenesis or during climatic periods of increased erosion of the continents (see, for instance, Veizer, 1989).

Strontium Isotope Age Curve for Marine Carbonate Rocks

The $^{87}Sr/^{86}Sr$ ratio of a carbonate mineral can be measured with great precision (that is to five significant figures). Workers at the Mobil (Oil) Field Research Lab successfully constructed a reference curve that traced the secular change in the Sr isotopic composition of seawater through all of Phanerozoic time (Burke and others, 1982; Elderfield, 1986; McArthur and Howarth, 2004; see figure 13). Index fossil samples were used to construct and constrain the original curve. Originally, the curve served as a reference for Sr isotope dating of marine carbonates without diagnostic index fossils. Cenozoic marine limestones and cherts can be dated with very small margins of error (for example DePaolo and Ingram, 1985; DePaolo, 1986; DePaolo and Finger, 1991) because of the availability of Cenozoic index fossils in good condition and the very steep, monotonic nature of the curve during this time period (figure 13). For older marine carbonates, dating is less accurate due to poor preservation of fossils as well as the oscillating trends of the Sr isotope age curve (figure 13). The amplitudes and high frequency of these oscillations over geologic time is probably the result of climatic, tectonic-erosional, and seafloor-spreading cycles (Allan and Wiggins, 1993). The Sr isotope curve is most useful for age dating during geologic time intervals when the curve is unidirectional and steep (for instance, during the Permian).

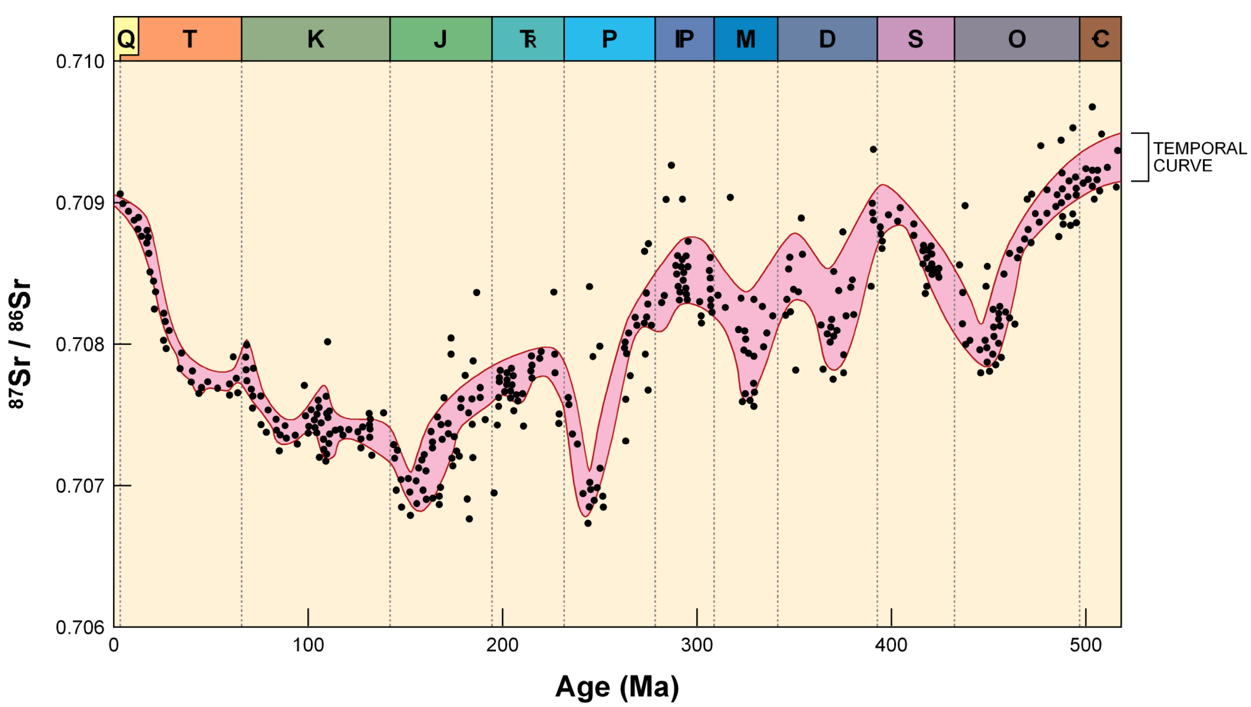

Figure 13. Strontium isotope seawater composition curve (from Burke and others, 1982; Elderfield, 1986; Allan and Wiggins, 1993).

Strontium Isotopes as Tracers for Diagenetic Fluids

Strontium isotopes can have significant value in tracing subsurface fluid movement (Burtner, 1987; Allan and Wiggins, 1993). Marine waters throughout geologic time apparently displayed a relatively narrow range of $^{87}Sr/^{86}Sr$ ratios - from about 0.7078 to 0.7095 (figure 13). Any ratios from carbonates that are significantly above or below this range of Phanerozoic seawater $^{87}Sr/^{86}Sr$ ratios indicate contribution by diagenetic waters in carbonate minerals that are of non-marine origin. Higher Sr isotope values indicate addition of radiogenic (high $^{87}Sr/^{86}Sr$ ratio) contaminants from crystalline (granitic or sialic) basement rocks or potassic feldspar-rich siliciclastic sediments (see, for instance Burtner, 1987). Lower Sr isotope values indicate contributions from mafics, ultramafics, and lithic sandstones with calcic plagioclase feldspar (see, for instance, Schultz and others, 1989).

Strontium is a doubly charged cation which easily substitutes into the carbonate crystal lattice (Allan and Wiggins, 1993). When Sr is released by diagenetic processes, it is partitioned into dolomites and carbonate cements in various subsurface settings (figure 14). Therefore, Sr analysis is an excellent tool for identifying hydrothermal dolomite.

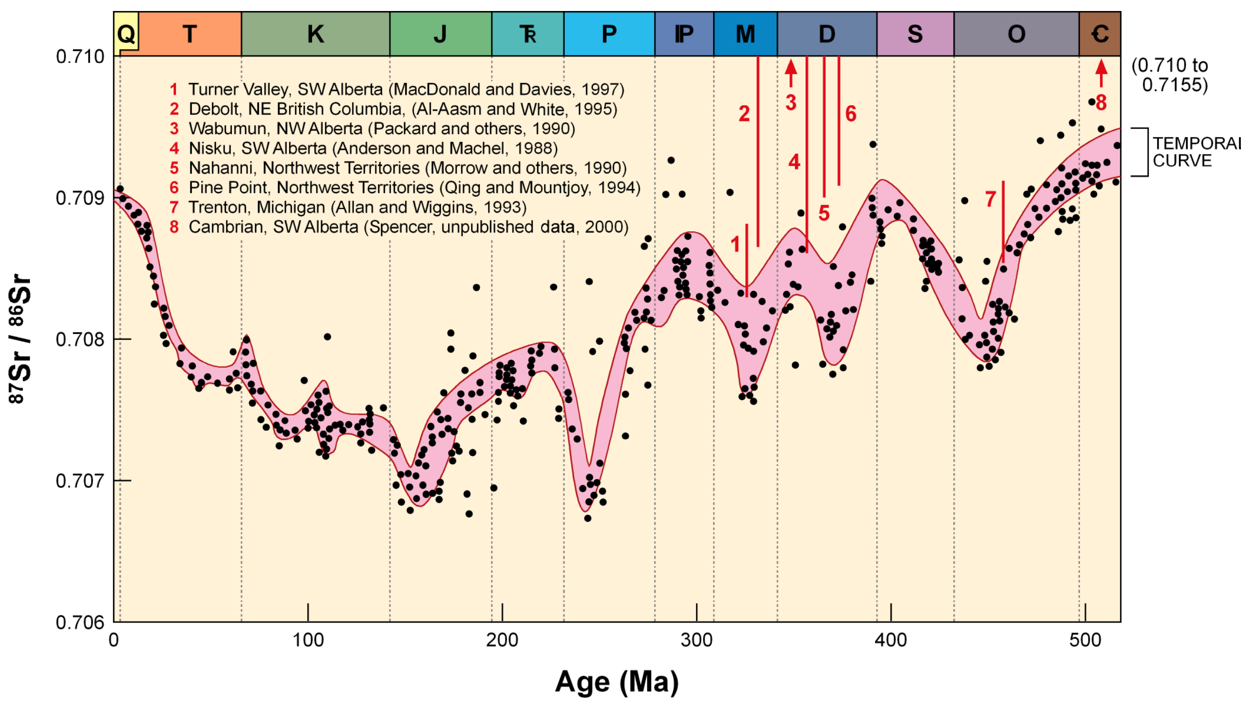

Figure 14. Strontium isotope compositions of saddle dolomites from the Canadian Rockies and Michigan Basin (from McArthur and Howard, 2004).

Strontium Isotopic Ratios for Leadville Samples at Lisbon Field

Three samples of different diagenetic mineral phases were selected for Sr isotopic analysis. Mineral separates were carefully drilled or plucked out of a conventional core segment from the Lisbon NW USA No. B-63 well, Lisbon field (figure 5), at a depth of 9939 feet (3030 m). One sample each of (1) replacement, brownish “sucrosic” (rhombic euhedral) dolomite, (2) coarse, white saddle dolomite, and (3) coarse, clear to white calcite spar cement (figure 15 is a thin section photomicrograph showing the same mineral phases from 9991.8 feet [3045.4 m]), were analyzed by Geochron Laboratories (a Division of Krueger Enterprises, Inc., Cambridge, MA) for $^{87}Sr/^{86}Sr$ isotopic ratios (table 2). The precision of these analyses was reported to six significant figures (that is 0.00000X).

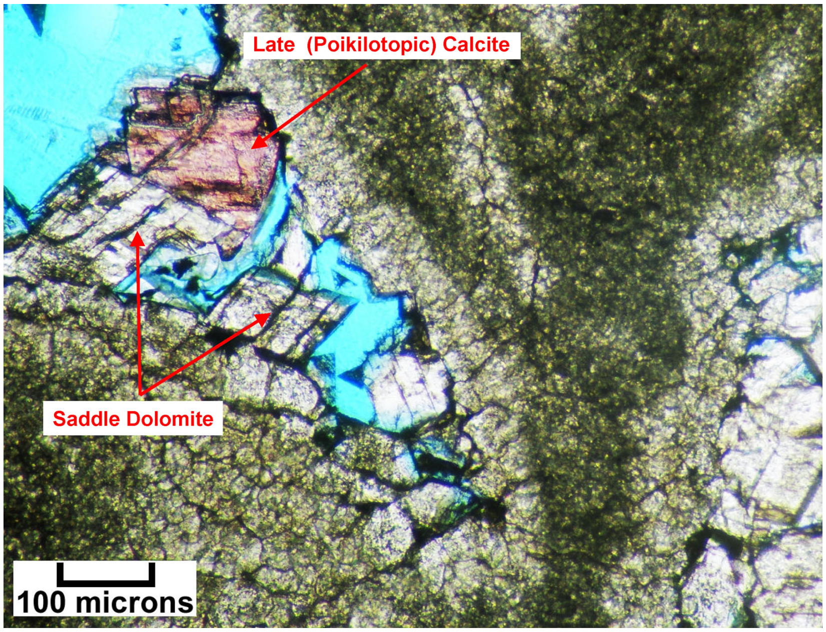

***Figure 15.** Photomicrograph (plane light) showing coarse, white saddle dolomite crystals and coarse, clear calcite spar cement (stained red) filling a portion of a large dissolution pore (blue) in a finely crystalline, sucrosic replacement dolomite matrix - the same diagenetic mineral phases found at the 9939-foot Sr sample depth. Lisbon NW USA No. B-63 well (figure 5), 9991.8 feet, porosity = 6.2 percent, permeability = 0.3 mD.*

***Table 2.** Strontium isotopic data from the Leadville Limestone in the Lisbon NW USA No. B-63 well core samples.*

Sample No.	Well	Depth (ft)	$^{87}Sr/^{86}Sr$	Comments
1	B-63	9939	0.712068	Late calcite
2	B-63	9939	0.711961	Saddle dolomite
3	B-63	9939	0.711464	Matrix sucrosic dolomite

All three samples exhibit highly radiogenic Sr isotopic values, each in excess of 0.711. These values are far higher than the secular range of $^{87}Sr/^{86}Sr$ ratios for marine carbonate fossils and rocks during the Mississippian or for any time during the Phanerozoic (Burke and others, 1982; Allan and Wiggins, 1993; Denison and others, 1994; Bruckschen and others, 1999; McArthur and Howarth, 2004). A plot of the Sr isotope composition for the three Leadville samples from Lisbon field, along with the Phanerozoic marine carbonate curve for Sr ratios, is shown in figure 16.

Discussion

It is apparent that the high Sr isotopic ratios for the three late (burial) diagenetic mineral phases indicate contributions from diagenetic waters enriched in ^{87}Sr that were derived from granitic or arkosic sandstone terrains. The most logical terrain for ^{87}Sr enrichment is either Precambrian basement rocks or the Devonian McCracken Sandstone. Both of these sources are at depths considerably below the Leadville reservoir rocks samples for this study. However,

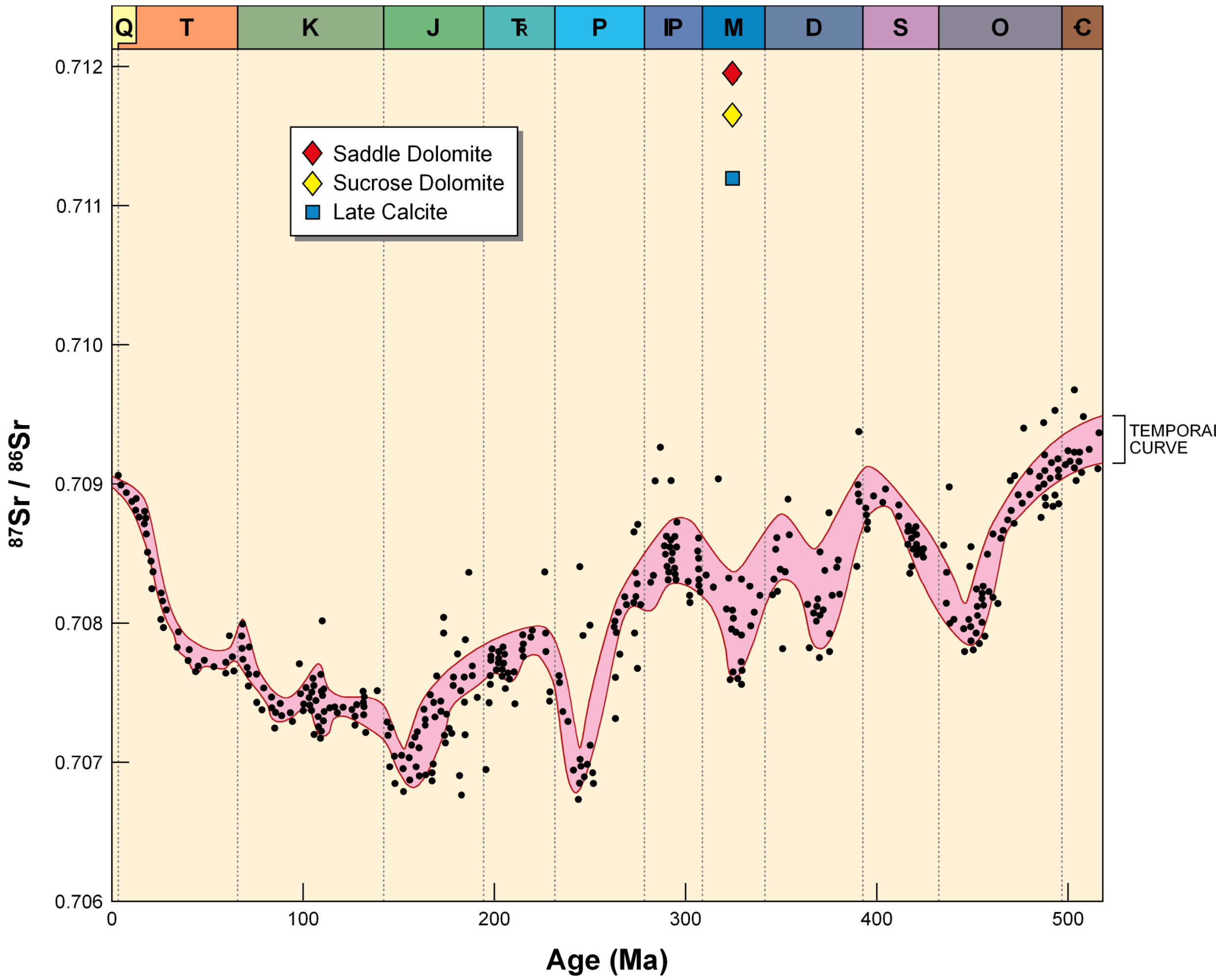

Figure 16. A plot of the Sr isotope composition for the three Leadville samples from Lisbon field along with the Phanerozoic marine carbonate curve for Sr ratios (modified from Allan and Wiggins, 1993).

early Tertiary reactivation of basement-involved, high-angle normal faults associated with Precambrian tectonics may have allowed hot, deep-seated fluids from the granitic basement or the McCracken Sandstone (figure 17) to communicate upwards with the Leadville carbonate section. Brines from evaporates in the Pennsylvanian Paradox Formation may also have entered the Leadville along the large fault bounding the northeast flank of Lisbon field (figures 5 and 17). It is interesting that these radiogenic fluids were involved in precipitation of replacement "sucrosic" dolomites, saddle dolomites, and late calcite spar cements.

Strontium isotope compositions from many (but not all) burial replacement dolomites are radiogenic (Allan and Wiggins, 1993, p. 95). The high $^{87}Sr/^{86}Sr$ ratio is indicative of allochtonous dolomitizing brines that interacted with potassic feldspars from basement rocks or from arkosic siliciclastic sediments prior to dolomitization. For instance, matrix replacement and white saddle dolomites in Upper Devonian (Frasnian) pinnacle reefs, Alberta Basin, Canada, surrounded by deeper-water facies, contain radiogenic Sr well above the Sr isotope seawater curve (Anderson, 1985; Allan and Wiggins, 1993, figure 95). Burial replacement dolomites in the Ordovician Trenton Formation of southern Michigan, also have Sr isotope

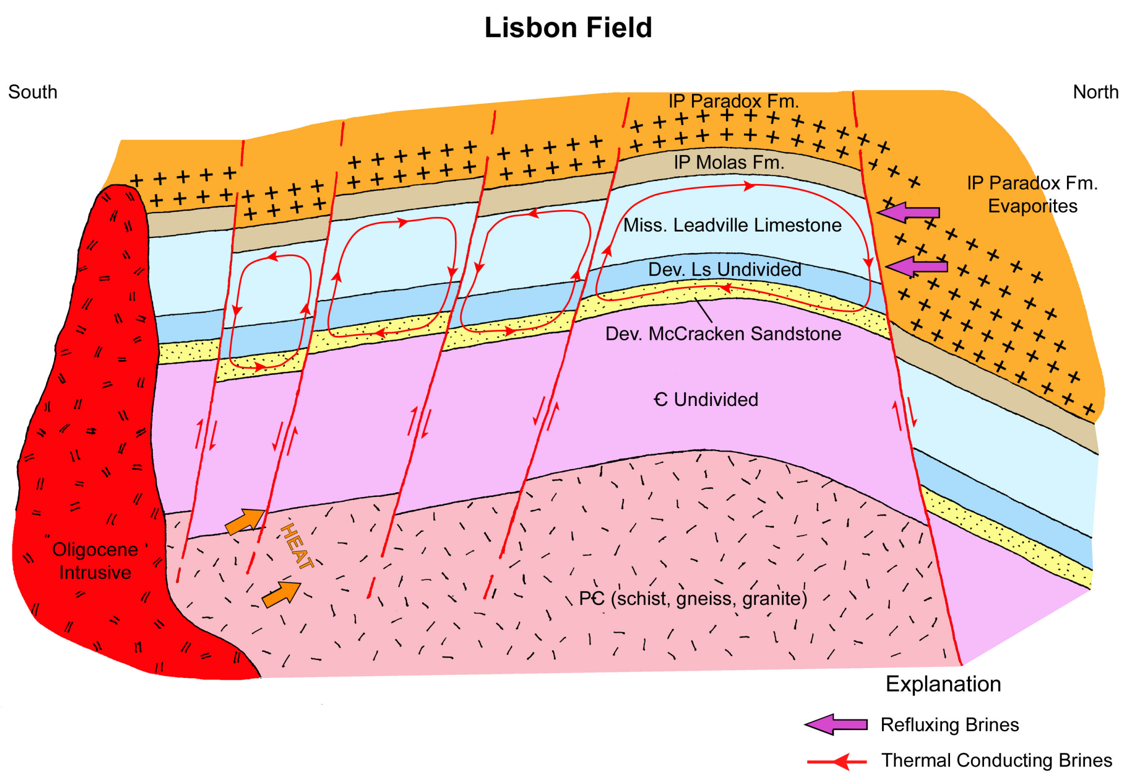

Figure 17. Possible heat sources and convection cells for late dolomitization of the Leadville Limestone in Lisbon field.

similarities to the Leadville at Lisbon field. Reactivation of a basement-involved, Precambrian, left-lateral wrench system allowed brines to migrate from the Silurian Salina Formation along faults and fractures into the Trenton (Allan and Wiggins, 1993). Strontium in Trenton limestone has Ordovician seawater values while dolomite has Silurian seawater values (figure 18).

Leadville Limestone Burial History and Possible Heat Sources

Burial history and temperature profiles for the Leadville at Lisbon field provide some guidance as to when important diagenetic and porosity-forming events occurred. These profiles (figure 19) were estimated using formation tops derived from well logs, a calculated geothermal gradient from bottom-hole temperatures of Lisbon wells, regional measured stratigraphic sections, geologic maps, and various publications summarizing the geologic history of the area. The burial history profile shows rapid burial during the Pennsylvanian corresponding to the development of the Paradox Basin. This period is followed by a relatively gradual increase in burial depth, with minor spikes representing times of erosion or non-deposition, until the rapid and maximum depth of burial (16,500 feet [5500 m]) occurred during the Late Cretaceous. The maximum temperature at this time was about 244ºF (118ºC). In addition to the calculated temperature profile, we have inferred anomalous temperature spikes for: (1) late Laramide reactivation along normal faults that extend to basement, and (2) Oligocene igneous events such as the emplacement of the nearby La Sal and Abajo laccolith complexes, 10 miles (16 km) north and 23 miles (37 km) southwest, respectively, of Lisbon field.

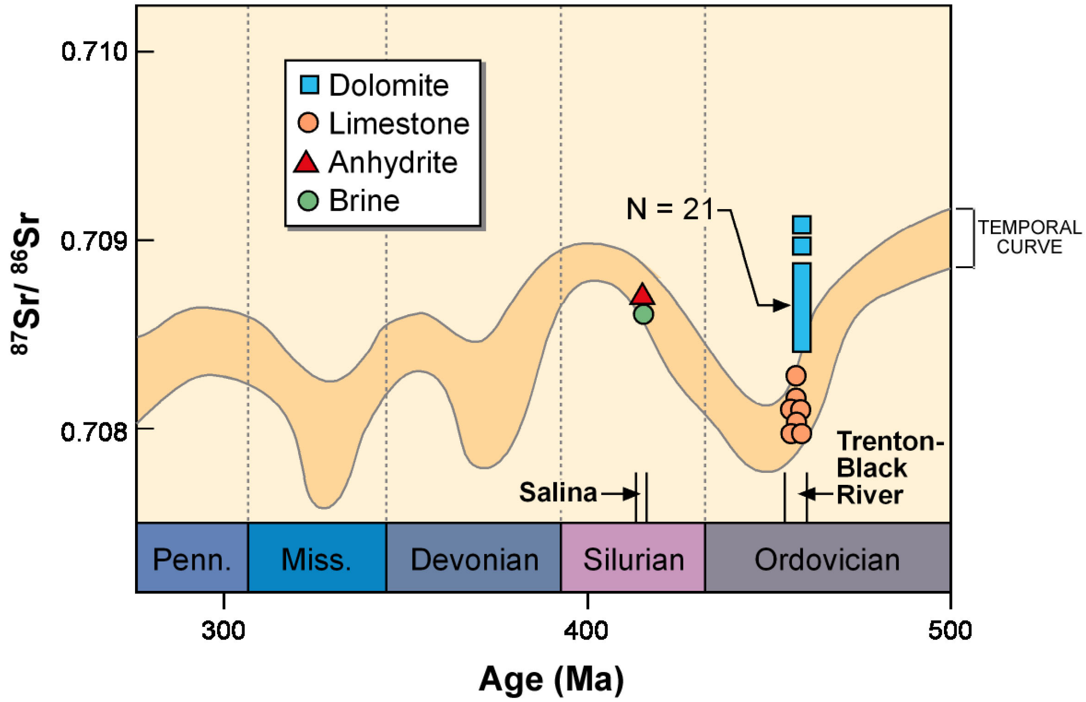

Figure 18. Strontium isotope values for limestone and dolomite of the Ordovician Trenton Formation and anhydrite and brine from the Silurian Salina Formation (from Allan and Wiggins, 1993).

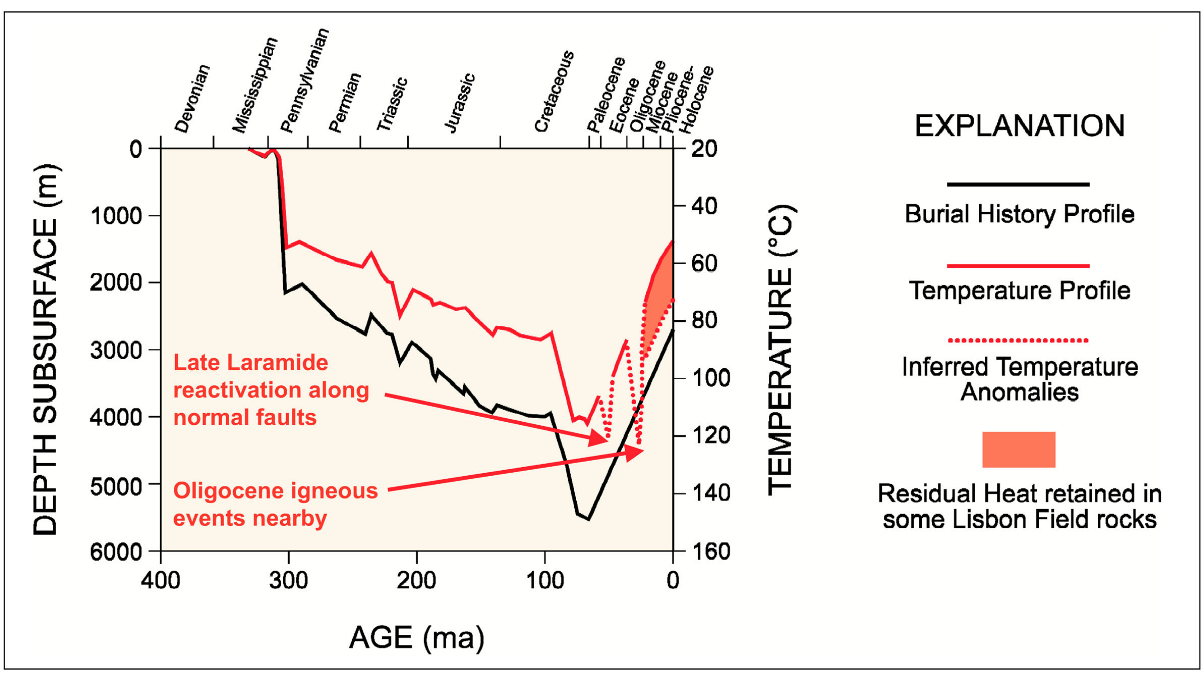

Figure 19. Burial history and temperature profile for Lisbon field.

Porous replacement dolomites probably formed during the early and middle portions of the burial history at Lisbon field. Figure 20 displays suggested windows for important diagenetic phases in the reservoir history of the Leadville Limestone at Lisbon field: (1) the formation of rhombic dolomites and major intercrystalline ("sucrosic") porosity, (2) saddle dolomite clear rims and cements, (3) euhedral quartz, dissolution of limestone and dolomite matrix, and pyrobitumen development, and (4) late calcite cements (with live oil inclusions). The inferred elevated temperature spikes during maximum burial, late Laramide fault reactivation/uplift, and Oligocene igneous activity may account for the high temperatures responsible for quartz precipitation, sulfide mineralization, pyrobitumen formation, late dissolution of carbonates, and late saddle dolomite cements.

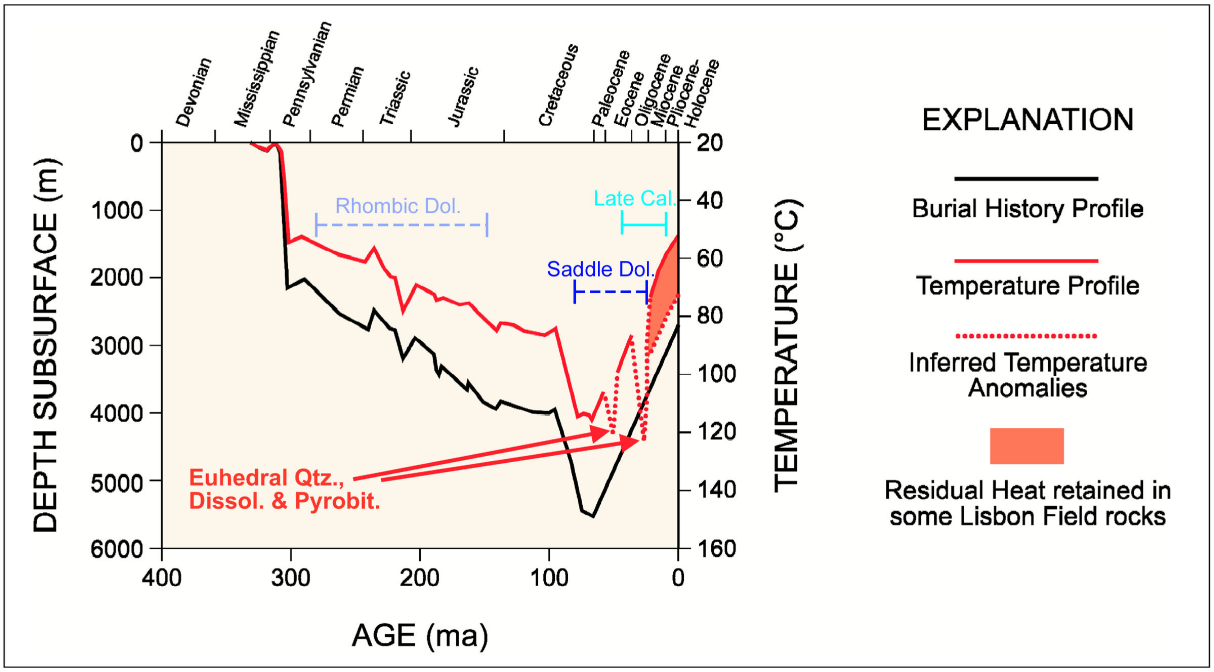

Figure 20. Burial history and temperature profiles with inferred diagenetic windows at Lisbon field.

We propose a model with convection cells bounded by basement-rooted faults to transfer heat and fluids from possible crystalline basement, Pennsylvanian evaporates, and Oligocene igneous complexes. Tremendous amounts of water are required to produce the amount, type, and generations of dolomite present at Lisbon field. There is probably not enough water moving through the regional hydrodynamic system to account for the Leadville dolomite. Recycling hot, brine-bearing water in convection cells may have allowed dolomitization to occur. A highly diagrammatic south to north cross section of the greater Lisbon field area (figure 17) shows the possible convection cells of the circulation model for ascending warm fluids responsible for saddle dolomite, high-temperature quartz, pyrobitumen, aggressive dissolution of limestone and dolomites, and sulfide mineralization. The basal aquifer for these inferred fault-controlled cells could be the Devonian McCracken Sandstone. This sandstone is locally porous enough to produce oil at Lisbon field. Sources of heat may have been from the Precambrian basement rocks and/or from Oligocene igneous intrusive activity. Some of the mapped faults cutting Lisbon field may have been involved with thermal convection cells for circulating fluids during late burial diagenesis (figure 21). Several wells near faults appear to have better reservoir quality, produce greater volumes of oil, and have higher residual bottom-hole temperatures than wells away from these faults.

TECHNOLOGY TRANSFER

The UGS is the Principal Investigator and prime contractor for the Leadville Limestone project, described in this report. All maps, cross sections, lab analyses, reports, databases, and other deliverables produced for the project will be published in interactive, menu-driven digital (Web-based and compact disc) and hard-copy formats by the UGS for presentation to the petroleum industry. Syntheses and highlights will be submitted to refereed journals, as appropriate, such as the *American Association of Petroleum Geologists (AAPG) Bulletin* and *Journal of Petroleum Technology*, and to trade publications such as the *Oil and Gas Journal*. This information will also be released through the UGS periodical *Survey Notes* and be posted on the UGS Paradox Basin project Web page.

The technology-transfer plan includes the formation of a Technical Advisory Board and a Stake Holders Board. These boards meet annually with the project technical team members. The Technical Advisory Board advises the technical team on the direction of study, reviews

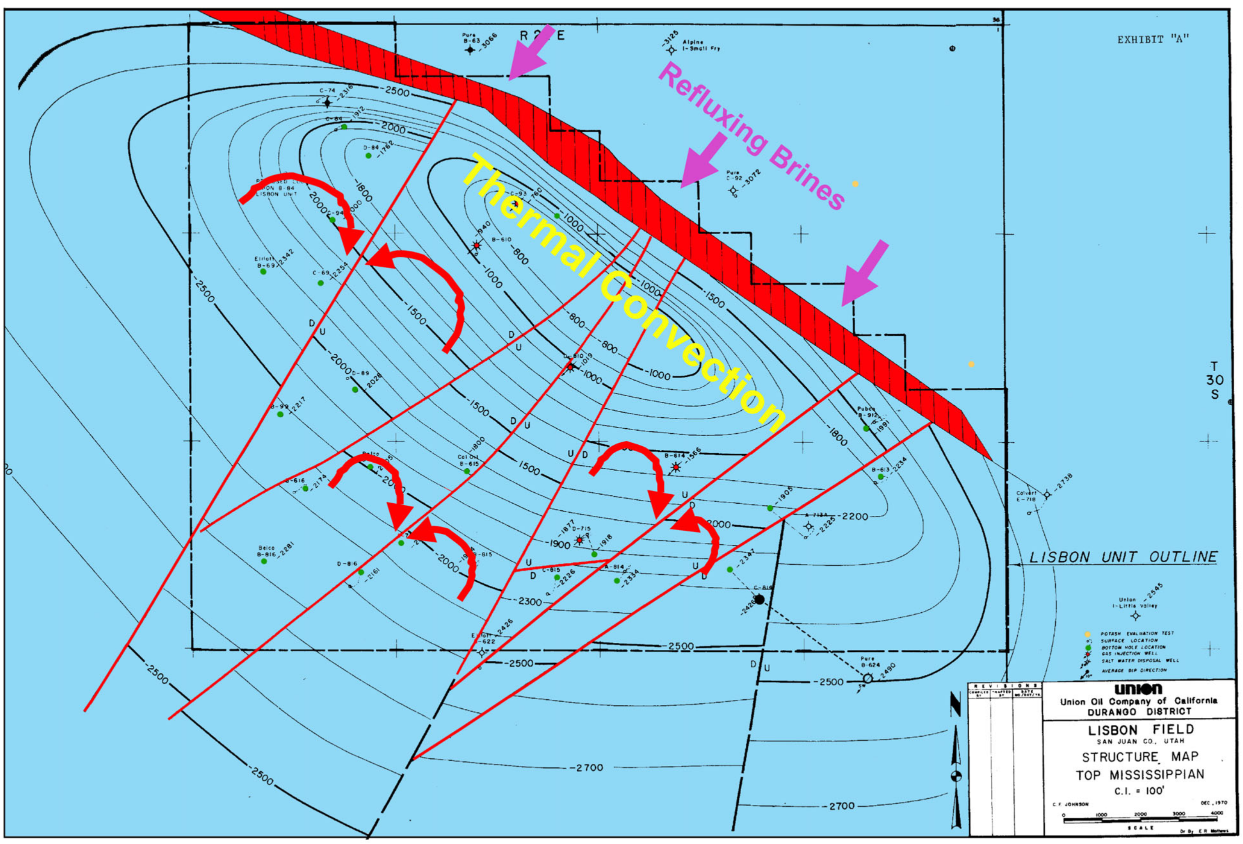

Figure 21. Top of structure of the Leadville Limestone, Lisbon field, showing possible thermal convection cells between small, northeast-southwest-trending normal faults (modified from C.F. Johnson, Union Oil Company of California files, 1970; courtesy of Tom Brown, Inc.).

technical progress, recommends changes and additions to the study, and provides data. The Technical Advisory Board is composed of Leadville field operators and those who are actively exploring for Leadville hydrocarbons in Utah and Colorado. This board ensures direct communication of the study methods and results to the operators. The Stake Holders Board is composed of groups that have a financial interest in the study area including representatives from the State of Utah (School and Institutional Trust Lands Administration, and Utah Division of Oil, Gas and Mining) and the federal government (Bureau of Land Management). The members of the Technical Advisory and Stake Holders Boards receive all semi-annual technical reports, copies of all publications, and other material resulting from the study. Board members also provide field and reservoir data.

Project materials, plans, objectives, and results were displayed at the UGS booth during the AAPG Annual Convention, June 19-22, 2005, in Calgary, Canada, and at the AAPG Rocky Mountain Section Meeting, September 23-24, 2005, in Jackson, Wyoming. Four UGS scientists staffed the display booth at these events. Project displays will be included as part of the UGS booth at professional meetings throughout the duration of the project.

An abstract describing Leadville diagenesis with emphasis on dolomitization was submitted and accepted for presentation at the 2005 Annual Convention of the Geological Society of America in Salt Lake City, Utah.

Utah Geological Survey *Survey Notes* and Web Site

The UGS publication *Survey Notes* provides non-technical information on contemporary geologic topics, issues, events, and ongoing UGS projects to Utah's geologic community, educators, state and local officials and other decision-makers, and the public. *Survey Notes* is published three times yearly. Single copies are distributed free of charge and reproduction (with recognition of source) is encouraged. The UGS maintains a database that includes those companies or individuals specifically interested in the Leadville project or other DOE-sponsored UGS projects. They receive *Survey Notes* and notification of project publications and workshops.

The UGS maintains a Web site on the Internet, http://geology.utah.gov. The UGS site includes a page under the heading *Oil, Gas, Coal, & CO_2*, which describes the UGS/DOE cooperative studies past and present (PUMPII, Paradox Basin [two projects evaluating the Pennsylvanian Paradox Formation], Ferron Sandstone, Bluebell field, Green River Formation), and has a link to the DOE Web site. Each UGS/DOE cooperative study also has its own separate page on the UGS Web site. The Leadville Limestone project page, http://geology.utah.gov/emp/leadville/index.htm, contains (1) a project location map, (2) a description of the project, (3) a reference list of all publications that are a direct result of the project, (4) poster presentations, and (5) semi-annual technical progress reports.

Presentations

The following presentations were made during the reporting period as part of the technology transfer activities:

"Current Oil and Gas Program of the Utah Geological Survey" by Thomas C. Chidsey, Jr., at the Society of Petroleum Engineers, Salt Lake Petroleum Section, "Gas and Oil

Developments in Utah: 2005 Update" symposium in Salt Lake City, Utah, May 20, 2005. The presentation reviewed DOE-funded UGS projects including the PUMPII, Class II Oil Revisit Paradox Basin horizontal drilling, and the Advanced and Key Oilfield Technologies for Independents (Area 2 – Exploration) Leadville Limestone studies (the subject of this report).

"Dolomitization of the Mississippian Leadville Reservoir at Lisbon Field, Paradox Basin, Utah" by David E. Eby, Thomas C. Chidsey, Jr., Craig D. Morgan, Kevin McClure, John D. Humphrey, Joseph N. Moore, Louis H. Taylor, and Virginia H. Weyland, at the AAPG Annual Convention in Calgary, Canada, June 20, 2005. The presentation included a poster display of the general petroleum geology of the Leadville Limestone, and facies, petrography, and diagenesis, especially dolomite, of the Lisbon case-study field in Utah.

Project Publications

Eby, D.E., Chidsey, T.C., Jr., Morgan, C.D., McClure, K., Humphrey, J.D., Moore, J.N., Taylor, L.H., and Weyland, V.H., 2005, Dolomitization of the Mississippian Leadville reservoir at Lisbon field, Utah [abs.]: American Association of Petroleum Geologists Annual Convention, Official Program with Abstracts, v. 14, p. A40.

Chidsey, T.C., Jr., Morgan, C.D., Eby, D.E., Moore, J., and Taylor, L. 2005, The Mississippian Leadville Limestone exploration play, Utah and Colorado: exploration techniques and studies for independents – semi-annual technical progress report for the period October 1, 2004 to March 31, 2005: U.S. Department of Energy, DOE/BC15424-3, 69 p.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

1. The Mississippian Leadville Limestone is a shallow, open-marine, carbonate-shelf deposit. The Leadville has produced over 53 million barrels (8.4 million m^3) of oil from six fields in the Paradox fold and fault belt of the Paradox Basin, Utah and Colorado. Most Leadville oil and gas production is from basement-involved structural traps. All of these fields are currently operated by small, independent producers. This environmentally sensitive, 7500-square-mile (19,400 km^2) area is relatively unexplored. Only independent producers continue to hunt for Leadville oil targets in the region.

2. Lisbon field accounts for most of the Leadville oil production in the Paradox Basin. Its reservoir characteristics, particularly diagenetic overprinting and history, and Leadville facies can be applied regionally to other fields and exploration trends in the basin. Therefore, Lisbon field was selected as the case-study field for the Leadville Limestone project.

3. Stable carbon and oxygen isotope data indicate that all Lisbon Leadville dolomites were likely associated with brines whose composition was enriched in del ^{18}O compared with late Mississippian seawater (several per mil heavier than normal seawater).

4. Stable oxygen isotope analyses of the Leadville replacement dolomites indicate that temperatures of precipitation ranged from about 60 to 90°C (~140-194 °F). Saddle dolomite cements were precipitated at temperatures greater that 90°C (>194 °F).

5. High Sr isotopic ratios for late burial diagenetic mineral phases at Lisbon field indicate contributions by waters enriched in ^{87}Sr that were derived from either granitic Precambrian basement rocks or the Devonian McCracken Sandstone.

6. Early Tertiary reactivation of basement-involved, high-angle normal faults associated with Precambrian tectonics may have allowed hot, deep-seated fluids from the granitic basement or the McCracken Sandstone to communicate upwards with the Leadville carbonate section. Brines from evaporates in the Pennsylvanian Paradox Formation may have also entered the Leadville along the large fault bounding the northeast flank of the field.

7. Burial history and temperature profiles for the Leadville at Lisbon field provide some guidance as to when important diagenetic and porosity-forming events occurred. Porous replacement dolomites probably formed during the early and middle portions of the burial history at Lisbon field.

8. Inferred elevated temperature spikes during maximum burial, late Laramide faulting/ uplift, and Oligocene igneous activity may account for the high temperatures responsible for quartz precipitation, sulfide mineralization, pyrobitumen formation, late dissolution of carbonates, and late saddle dolomite cements.

9. We propose a model with thermal convection cells bounded by basement-rooted faults to transfer heat and fluids from possible crystalline basement, Pennsylvanian evaporates, and Oligocene igneous complexes.

10. We recommend that any evaluation of the Leadville Limestone include stable carbon and oxygen isotope analysis of diagenetic components, strontium isotope analysis for tracing the origin of fluids responsible for different diagenetic events, and production of burial history and temperature profiles to help determine when the diagenetic events occurred.

ACKNOWLEDGMENTS

Funding for this research was provided as part of the Advanced and Key Oilfield Technologies for Independents (Area 2 – Exploration) Program of the U.S. Department of Energy, National Petroleum Technology Office, Tulsa, Oklahoma, contract number DE-FC26-03NT15424. The Contracting Officer's Representative is Virginia Weyland. Support was also provided by Eby Petrography & Consulting, Inc., Littleton, Colorado, and the Utah Geological Survey (UGS).

Core and petrophysical data were provided by Tom Brown, Inc. (now Encana Corp.).

James Parker of the UGS drafted figures and Cheryl Gustin, UGS, formatted the manuscript. This report was reviewed by David Tabet and Robert Ressetar of the UGS.

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